Smart Sensors' Role in Integrated System Health Management

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Introduction

During the last decade, there has been a major effort in the aerospace industry to reduce the cost-per-pound of payload and become competitive in the international market. Competition from Europe, Japan, and China has reduced this cost to almost a third from 1990 to 2000. This cost has leveled in recent years to an average price of around $12,000/pound of payload. One of NASA's goals is to promote the development of technologies to reduce this cost by a factor of 10 or more

Exploration of space, specially manned exploration missions, involves very complex launch and flight vehicles, associated ground support systems, and extensive human support during all phases of the mission. When considering the Space Shuttle Program, we can see that vehicle and ground support systems' processing, operation, and maintenance represent a large percentage of the program cost and time. Reducing operating, processing and maintenance costs will greatly reduce the cost of Exploration programs.

The Integrated System Health Management (ISHM) concept is one of the technologies that will help reduce these operating, processing and maintenance costs. ISHM is an integrated health monitoring system applicable to both flight and ground systems. It automatically and autonomously acquires information from sensors and actuators and processes that information using the ISHM-embedded knowledge. As a result, it establishes the health of the system based on the acquired information and its prior knowledge. When this concept is fully implemented, ISHM systems shall be able to perform failure prediction and remediation before actual hard failures occurs, preventing its costly consequences.

Data sources, sensors, and their associated data acquisition systems, constitute the foundation of the system. A smart sensing architecture is required to support the acquisition of reliable, high quality data, required by the ISHM. A thorough definition of the smart sensor architectures, their embedded diagnostic agents, and communication protocols need to be established and standardized to allow the embedding and exchange of health information among sensors and ISHM.

This workshop is aimed to foster the exchange of ideas and lessons learned between government, industry and academia to aid in the establishment of ISHM (and smart sensors) standards and guidelines as well as to identify present technology gaps that will have to be overcome to successfully achieve this goal.

Definition of a Smart Sensor

Defining what a Smart Sensor is has been a struggle through the years. The amount of "*smarts*" that a sensor should have has been loosely defined by industry, ranging from a digital communication interface to the external world to complex processes embedded in sensors. The Institute of Electrical and Electronics Engineers (IEEE) defines in its standard IEEE 1451.1 (page 12) what they consider a smart transducer. It says as follows:

> *3.134 Smart Transducer: "A transducer that provides functions over and above that necessary for generating a correct representation of a sensed or controlled physical quantity. This functionality typically simplifies the integration of the transducer into applications in a networked environment."*

In reality the IEEE standards describes a detailed architecture for smart transducers. It is specially detailed describing the communication mechanisms to be used by smart transducers. The main goal of IEEE 1451 is to develop an architecture that is networked and vendor independent with a common transducer interface. This feature will allow transducers to be easily installed, removed,

and/or replaced. It will also minimize any reconfiguration errors. The standard advocates for common approach to general transducer data, control, timing, configuration, and calibration templates. Information related to these templates is contained in Transducer Electronic Data Sheets (TEDS) at the transducer.

Characteristics of a Smart Sensor

There are many characteristics that are desired in Smart Sensors. Self-identification is probably the first characteristic being sought and readily implemented by industry. Configuration control is required in most applications, especially in complex systems. Configuration control is normally implemented using documentation and it is verified by operator's visual inspection in present applications. An automated self identification feature is highly desirable and very cost effective.

Another characteristic being sought in Smart Sensors is to transfer some of the system's intelligence into the sensor. Data conversion and digitization in sensors is a first step. Sensors can provide digital output data already converted into engineering units to their associated systems thus allowing these systems to perform other more important and complex tasks. Time stamping and data synchronization is another desirable characteristic that can be implemented in a Smart Sensor. Additional complex signal processing (trending, averaging, etc) and data storage can be added to the Smart Sensor to provide for enhanced capabilities.

Our efforts in the area of Smart Sensors development have been focused in assuring "*data validity*" and "*data availability*". One of the most important requirements of any sensor is to provide the associated system with data that is valid at all time. Another essential requirement of sensors is to always provide data to the system when it is needed (assure data availability). Implementation of both of these requirements is complex in nature.

A Smart Sensor shall be capable to continuously assess the validity of the data being produced and qualify it with a measurement of data validity. Sensor self-health assessment is one of the processes that can be embedded in sensors to accomplish this. Several self-health assessment algorithms can be implemented in sensors. Auto-calibration capability is one method to verify the sensor capability to provide accurate data. The Smart Sensor should verify its calibration and assess the validity of the data provided. Statistical tools can also be implemented in sensors to verify data validity.

Data availability can be provided by a combination of hardware and software in the Smart Sensor. Self-reconfiguration capability can be implemented in the sensors to allow the removal and replacement of faulty components in the Smart Sensor with spare components. The combination of self-calibration and self-reconfiguration capabilities in sensors allows for an increased probability of data availability. Another possible implementation is the use of multi-sensor arrays and embedded statistical tools to provide the added assurance of data availability. Most of the possible implementations described here have been prototyped in the Instrumentation Laboratory at Kennedy Space Center with positive results.

Finally, a combination of embedded algorithms can be implemented in these Smart Sensors to provide the desired "health management" capability. A proposed Health Electronic Data Sheets (HEDS) approach is presented where health parameters are calculated, monitored and stored in the Smart Sensors to aid in the determination of the sensor's health. Some of these parameters are: averaging, trending, rate of change, sampling, calibration, etc.

KSC Smart Sensor Architecture

KSC Smart Sensor architecture is shown in Figure 1. Smart Sensors can transmit information to other Smart Sensors or the next higher layer (Knowledge Base system) that constitutes the ISHM system (See Figure 2). The interface between Smart Sensor-to-Smart Sensor and Smart Sensor-to-next higher layer (system) is performed based on a network configuration. This architecture has the capability to communicate, not only an upward/downward information exchange (sensors to system and system to sensors) but also among the associated peers (sensors to sensors).

The Smart Sensor is composed of an Intelligent or Smart Sensor Agent (SSA) that is responsible for checking the sensor health and validating the sensor data provided to the ISHM Knowledge Base. The embedded intelligence in the SSA will allow the sensors to assess their health,

to identify themselves within the system, to know which other sensors are associated with their processes, and to assess the validity of the data they provide by crosschecking themselves with their associated peers. This architecture accounts for the possibility of having several raw sensing devices attached to a single SSA (See Figure 1).
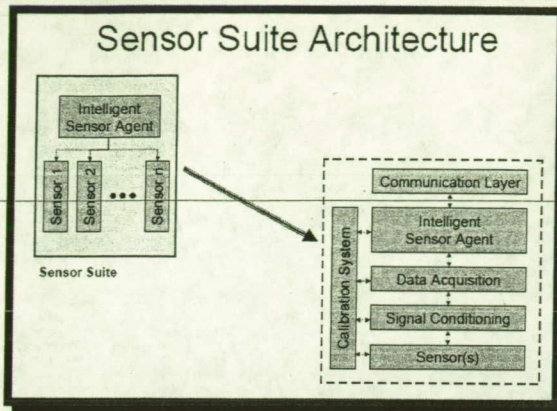

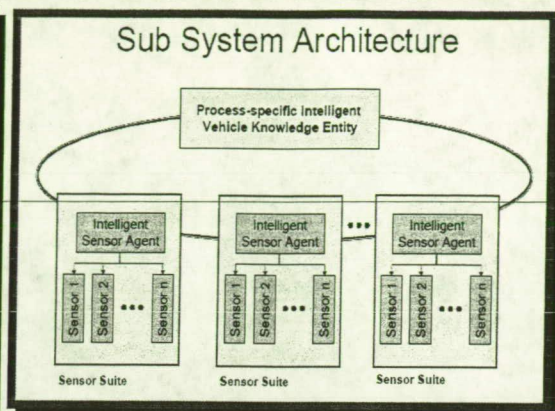**Figure 1.- KSC Smart Sensor Architecture**

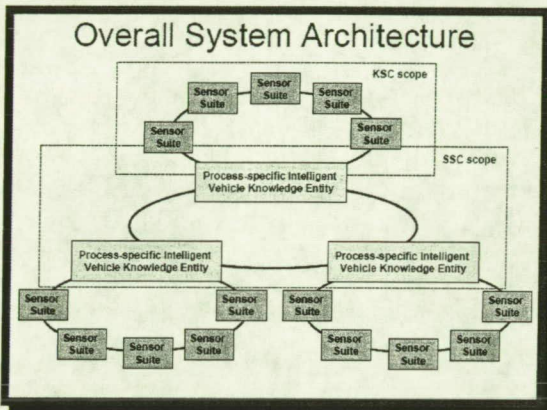**Figure 2.- KSC Sub System Architecture**

Figure 3.- Overall System Architecture

The communication layer defines the interface to other Smart Sensors and to the next higher layer (system). This architecture is designed to meet IEEE 1451 requirements, but flexible to accommodate other approaches. A proposed network configuration is Ethernet-based using UDP or TCP/IP protocol. Another possible network approach uses wireless communication with KSC developed protocols.

The raw sensor(s) interfaces to a Signal Conditioning stage that provides the excitation source(s) and conditions the signal(s). The Data Acquisition stage converts the signal from analog to digital and also acquires other parameters of interest (i.e. temperature for thermal compensation, etc). The calibration stage will continuously monitor the Smart Sensor and periodically verify its calibration and health. One of the SSA responsibilities is to validate the data provided by the sensor as good. To do this, the SSA performs sensor data trending, checks for boundaries within known states, and verifies its actual output with associated smart sensors in the process. Other statistical, empirical, and logical rules can be also used to verify that the data transmitted to the system is valid and accurate. Other features or tasks of the SSA are related to configuration control issues (Sensor ID, calibration date, calibration parameters, next calibration due date, etc). All this information is formatted per IEEE 1451 guidelines. Refer to Figures 4 and 5.
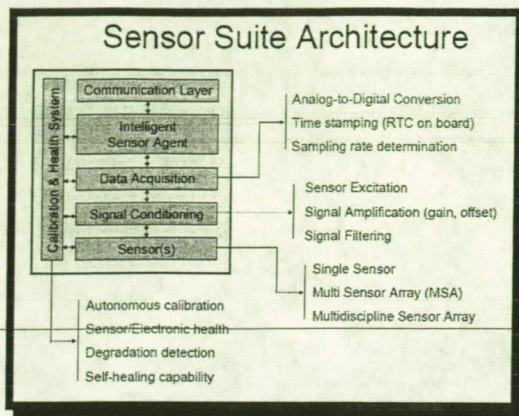
Figure 4

Sensor Suite Architecture

Calibration & Health System

- Communication Layer
- Intelligent Sensor Agent
- Data Acquisition
- Signal Conditioning
- Sensor(s)

Data Acquisition:
- Analog-to-Digital Conversion
- Time stamping (RTC on board)
- Sampling rate determination

Signal Conditioning:
- Sensor Excitation
- Signal Amplification (gain, offset)
- Signal Filtering

Sensor(s):
- Single Sensor
- Multi Sensor Array (MSA)
- Multidiscipline Sensor Array

Calibration & Health System:
- Autonomous calibration
- Sensor/Electronic health
- Degradation detection
- Self-healing capability

Figure 4.- Responsibility Assignments

Figure 5

Sensor Suite Architecture

Calibration System

- Communication Layer
- Intelligent Sensor Agent
- Data Acquisition
- Signal Conditioning
- Sensor(s)

Communication Layer:
- Standardized communication protocol (i.e. TCP over Ethernet)

Embedded Knowledge:
- Provides accurate and reliable data
- Conducts Sensor Suite health checks
- Communicates with other sensor suites to validate data and health of the sensor(s)
- Contains sensor identification and characterization parameters
- Contains parameters to perform sensor validation and measurement interpretation
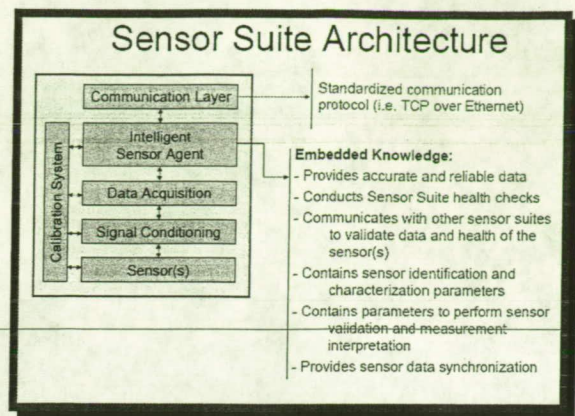- Provides sensor data synchronization

Figure 5.- Responsibility Assignments

KSC Precursors to Smart Sensors

Advanced Data Acquisition System (ADAS)

The architecture presented here displays an innovative approach to data acquisition systems. The design incorporates: electronic health self-check, device/system self-calibration, electronics and function self-repair, failure detection and prediction, and power management (reduced power consumption). The architecture incorporates some commercially available components, such as Field Programmable Gate Arrays (FPGA), Programmable Analog Integrated Circuits (PAC IC), Field Programmable Analog Arrays (FPAA), and Digital Signal Processing (DSP) electronic/system control.

ADAS is composed of three main sections. They are the following: (a) Analog Signal Module Section, (b) Digital Signal/Control Module Section and (c) Power Management Module Section.

Patent rights have been granted to Kennedy Space Center under U.S. patent # 6,462,684. NASA KSC commercialization office has also issued licensing rights to Circuit Avenue Netrepreneurs.
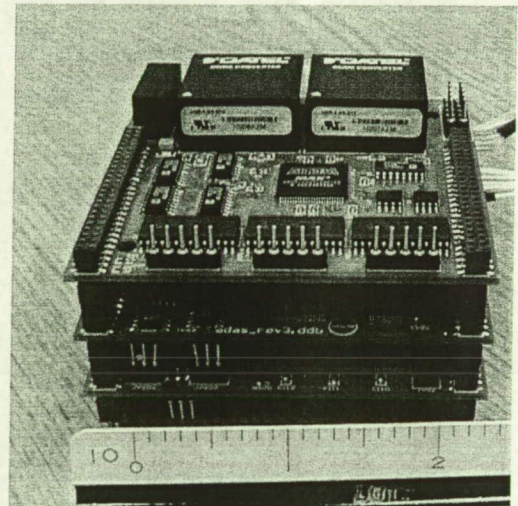
Picture 1.- Example of 4-channel ADAS

Valve Health Monitor (VHM)

Health of electromechanical systems, specifically solenoid valves, is a primary concern at KSC. The potential of delaying scheduled launch of vehicles and/or personnel injury due to failure of electromechanical systems requires the program to continuously disassemble, inspect and test valves to assure their readiness. Disassembly inspection and testing of these systems pose an additional potential risk of hardware failure.

The VHM is a non-intrusive device capable of continuously and autonomously monitor the health and performance of valves during operation. It can be trained to detect degradation and/or potential problems before they happen.

The VHM in-situ determines the health and performance of a solenoid valve by processing the electrical current signature of the solenoid valve. Embedded smart algorithms are processed by an on-board DSP, monitoring peaks and valleys of the electrical current in the solenoid valve and recording time, slopes and magnitudes. The method also has the capability of comparing processed information to a historical profile or a learned profile. The VHM provides notification to the operator when out of specification conditions are encountered.

A patent application has been filed with the Patents and Trademarks Office for this invention. Furthermore, NASA KSC commercialization office has issued licensing rights to Schaffer, Inc.
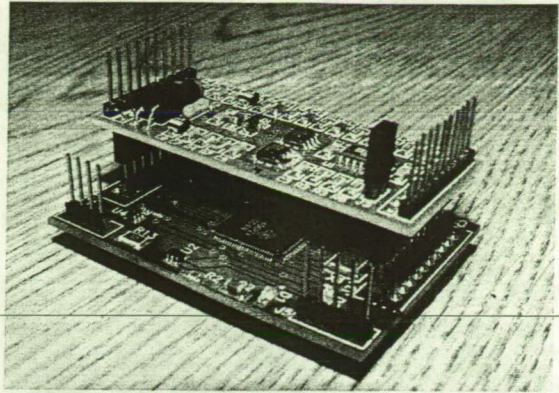
Multi-Sensor Array (MSA) Pressure Transducer

A novel approach has been developed that integrates an array of eight independent pressure sensors into a single housing of equivalent size to currently used at the Space Shuttle launch pads. The optimal number of pressure sensor elements (pressure array) is defined by the individual reliability assessment of the pressure sensor elements and physical constraints of the overall sensor. An on-board processor uses a smart algorithm to determine the health status of the eight elements, sends out a single weighted average of all devices, and reports the overall health of the sensor. Using the MSA algorithm, the transducer also "learns" (it has a history for each sensor element) which sensing elements it may trust and which may be unreliable. In this manner, the transducer may be installed at a remote site and will not be recalibrated until the device reports an approaching need whose tolerances are set by the user's discretion.

Picture 2.- Example of VHM processor

Picture 3.- Example of VHM sensor head

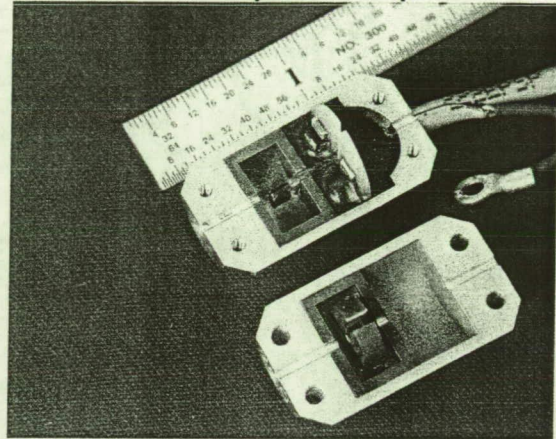Picture 4.- Example of MSA pressure transducer

Patent rights have been granted to Kennedy Space Center under U.S. patent # 6,757,641. NASA KSC commercialization office has also issued licensing rights to TABER Industries.
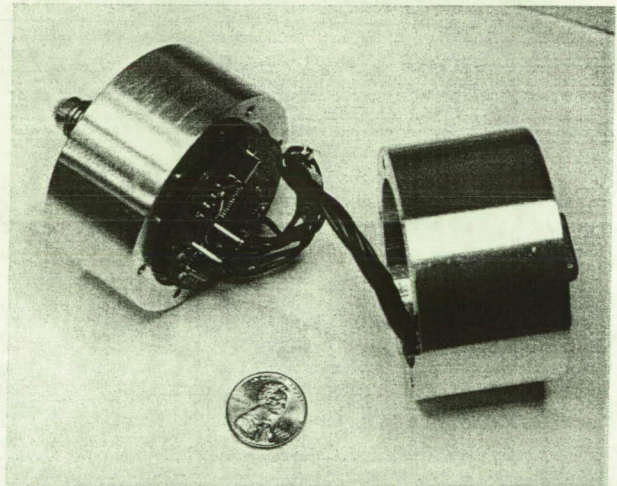
Hydrogen/Oxygen Leak Detection Point Sensor

Kennedy Space Center has been collaborating with Glenn Research Center, Case Western Reserve University and MAKEL Engineering in the development of a hydrogen/oxygen leak detection
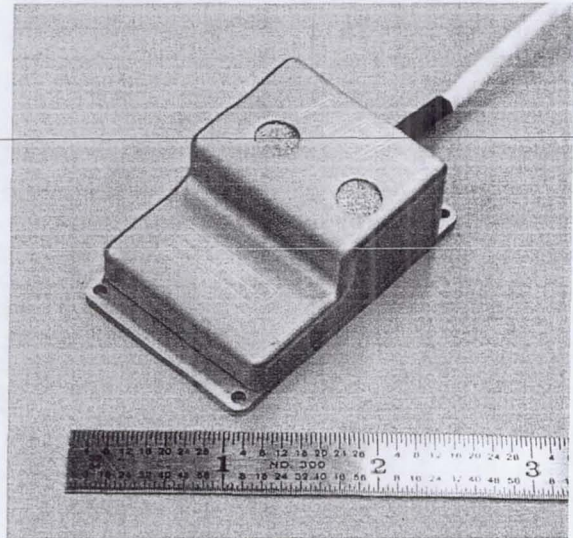
point sensor. The device contains four sensing elements (hydrogen, oxygen, pressure and temperature) connected to an on-board processor. Embedded smart algorithms process the data from the sensing elements and calculate the leak concentration for different environments (changing pressure, temperature and gas backgrounds). The device communicates to the next higher assembly (system) through RS-485 communication protocols. This development is being tested at KSC at the present time.

Benefits of Smart Sensors over Traditional Sensors

Many benefits can be attributed to Smart Sensors when compared to traditional sensors, among them we can mention:

- **Data validity and availability**: Smart sensors' embedded knowledge will allow for the validation of its data. This function is currently performed by higher entities in the system. Data availability is enhanced by the ability of the Smart Sensors to detect failures and reconfigure upon failure detection.
- **Distributed knowledge and processing:** Smart Sensors have the capability to locally process data and to provide the system with measurement and sensor's health information. This capability unloads the higher levels of the

Picture 5.- Example of MAKEL Hydrogen sensor

system of this burden allowing them to perform other important tasks. This capability also reduces the required system bandwidth.
- **Robustness**: The overall system becomes more robust when the effects of the failure of one of its components are minimized by the ability of other smart components in the system to overcome and compensate for the failure.
- **Reliability/ Maintainability**: Reliability is highly enhanced by the ability of Smart Sensors to autonomously check their health and to reconfigure/heal themselves upon failure detection. Autonomous monitoring, health checking, and self-healing capabilities also can minimize the requirement for human maintenance, interface, and interaction with these systems.
- **Reusability**: Standardization will be a key feature of reusability. Flexible architectures based on electronic components such as FPGA, FPAA, and DSP will allow not only for the reusability of these systems but will greatly reduce the logistical needs of the program.
- **Autonomy and Reconfigurability:** This approach (embedded intelligence, self-calibration and self-healing capabilities) allows systems to operate autonomously with minimal human intervention. Furthermore, allows systems to re-adapt to new roles (new measurements parameters) as well as to reconfigure themselves upon failure detection.

Smart Sensors Networks

The arrangement of Smart Sensors in a network type configuration is the logical step to fully utilize the added capabilities of this approach. Communication between sensor and next higher assembly (system) is no longer constrained by a single wire connection. Smart Sensors can not only send data to the system but also to associated Smart Sensors in the network. Information from the system such as sensor/system configuration, sensor/system health, and process status can be easily shared by sensors and higher layers in the system. Sharing of process states and transitions can also be performed. System does not degrade if connection between a sensor and the system is damaged; other communication paths are created and used.

Although the primary means of connecting sensors in a network configuration has been established using wires (Ethernet, RS-485, etc), other configurations such as wireless have been

successfully used. KSC has successfully demonstrated a Wireless Sensor Network approach at Space Shuttle launch pad A.

Role of Smart Sensors in Integrated System Health Management

As previously discussed in this paper, Smart Sensors play a very important role in the Integrated System Health Management approach. Some of the roles discussed are:
- Provide valid data (assess and qualify the validity of the data)
- Provide processed data (data conversion and compensation)
- Provide sensor health status (potential degradation and failures)
- Provide embedded self-healing capabilities (self-calibration and self-reconfiguration)
- Provide sensors networking capability (wired and wireless)
- Provide higher reliability and longer calibration cycles
- Provide automation and autonomy, reducing human intervention (reduced maintainability costs)

These are some of the roles and characteristics that Smart Sensors bring to the ISHM architecture that enhance the operation, maintenance, reliability, and autonomy of such a system.

Summary/Conclusions

The Integrated System Health Management (ISHM) approach presents a great opportunity for vast enhancements in reliability, cost reduction in vehicle, and surface support equipment maintenance and operational costs. It also presents a major leap on safety improvements for future space exploration missions. NASA has recognized the potential of intelligent health technologies and has supported development of specific subsystems and component technologies; ISHM is also an emergent core technology for many of the most advanced commercial and military avionic platforms. Ultimately, ISHM technologies will be the monitoring and control backbone in vehicles and ground support facilities for Moon and Mars exploration.

The Integrated System Health Management (ISHM) architecture consists of traditional and smart sensors, intelligent algorithms, and data processing that enable the monitoring and management of diverse systems. The ISHM effort supports the goals of *autonomy, modularity, re-configurability,* and *data-rich virtual presence* desired by the Exploration program. Accordingly, Smart Sensors are designed and developed following the same criteria. ISHM supports determination of nominal/off-nominal behavior so that other systems can take appropriate actions. Smart Sensors support that role by performing sensors' specific tasks, assigned by ISHM, to optimize the performance of this effort. The combination of Smart Sensors and ISHM technology presents the optimal approach to vehicle and surface support system health management.

Acknowledgments